Interpretation of Long-term Conservation Agriculture and Green Manure Cover Crop Systems

1. Yield Performance

- Baseline wheat yield (no advanced management): **6,760 kg/ha**.
- With full conservation package (short-term fallow, reduced tillage, ridge planting, cover crops): yield increased to **8,489 kg/ha** (+24%).
- Best-performing single cover crops:
  - **Forage millet**: 9,518 kg/ha
  - **Sudangrass**: 9,029 kg/ha
  - **Mung bean and canola**: 8,918 kg/ha
- Mixtures also showed strong benefits, especially **safflower–forage millet**, which reached **10,740 kg/ha** in the second season.
- In comparison:
  - **Manure**: 7,710–8,120 kg/ha (less effective, variable across years)
  - **Weedy fallow**: 7,690–8,330 kg/ha (slightly positive in water-limited summers but poor for soil carbon).

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2. Soil Quality Improvement

- **Soil Organic Carbon (SOC)** increased from **0.45% → 0.81%** within 3 years.
- Soil organic matter rose from **0.78% → 1.40%** by year 4.
- Improvements noted in:
  - Cation exchange capacity (CEC)
  - Porosity and aggregate stability
  - Soil color (biological activity)
  - Water-holding capacity (allowing irrigation intervals to double).
- These changes directly reduced irrigation water requirements by **~50%**.

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3. Economic Impact

- Average cost of wheat + cover crop production: **145 million IRR/ha** (mostly from wheat).
- Net income from wheat: **111 million IRR/ha**.
- Best treatment: **forage millet cover crop** (124 million IRR/ha net return).
- Average profitability indicators:
  - Return on Sales: **~39%**
  - Return on Investment: **~65%**
  - Best for forage millet: **42%** and **73%**, respectively.

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4. Role of Fallow and Weed Management

- Using **weedy fallow** instead of clean fallow (when summer irrigation is impossible) increased wheat yield from **6,760 → 10,171 kg/ha** after four years.
- However, SOC balance was **negative**, indicating soil nutrient depletion and risk of degradation.
- Integrating **short fallow (45 days) + green manure cover crop (60–65 days)** was more sustainable:
    - Slightly lower yield but **positive SOC balance**, preserving soil fertility.

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5. Legacy Effects (Carry-over Benefits)

- Green manure cover crops showed **persistent effects** (legacy) on subsequent wheat:
    - Example: **Safflower–millet** consistently improved yield in both years.
    - Example: **Oat–safflower** improved only in year two, suggesting delayed root/allelochemical effects.
- Correlation analysis:
    - **93.6%** of wheat yield variation explained by combined biomass of cover crops + weeds.
    - **90.9%** explained by cover crop biomass alone.
    - **56.6%** explained by weed biomass alone (weaker, less reliable).

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6. Biological and Microbial Mechanisms

- **Forage millet** contributed via **Biological Nitrification Inhibition (BNI)**, reducing nitrate leaching and preserving N for wheat.
- Soil microbial community enhanced by cover crops supported:
    - Nutrient cycling and N fixation
    - Root exudate–driven hormonal balance (auxins, cytokinins, gibberellins)
    - Pathogen suppression and improved disease resistance
    - Stress tolerance to drought/salinity.

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7. Ranking of Main Drivers

Driver	Impact on Wheat Yield & Soil Health
Cover crop species/mixtures	Very strong (up to +3,500 kg/ha vs. controls).
Soil Organic Carbon build-up	Strong link to yield, water savings, nutrient retention.
Water management (short fallow + cover crop vs. weedy fallow)	Determines sustainability of yield gains.
Legacy effects	Some species act quickly (safflower, millet), others need >1 season (oat, safflower).
BNI mechanism (forage millet, sorghum)	Reduces N losses, improves N-use efficiency.

Driver	Impact on Wheat Yield & Soil Health
Microbial activity	Indirect but crucial role in nutrient availability, resilience.

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8. Final Synthesis

- **Best system identified:** *Mixed safflower–forage millet green manure cover crop* (high yield, strong soil improvement, water-use efficiency).
- **General rule:** Both monoculture and mixture cover crops are useful, but mixtures (esp. safflower-based) maximize performance.
- **Environmental co-benefits:** Higher SOC, lower irrigation demand, reduced dependence on chemical inputs.
- **Recommendation:** Integrating cover crops into wheat-based irrigated systems in semi-arid regions offers **a holistic solution** for productivity, sustainability, and resilience against soil and climate challenges.

a **summary decision table** ranking the cover crops and mixtures by **(1) yield effect, (2) soil improvement potential, and (3) economic return**, based on the multi-year results you provided.

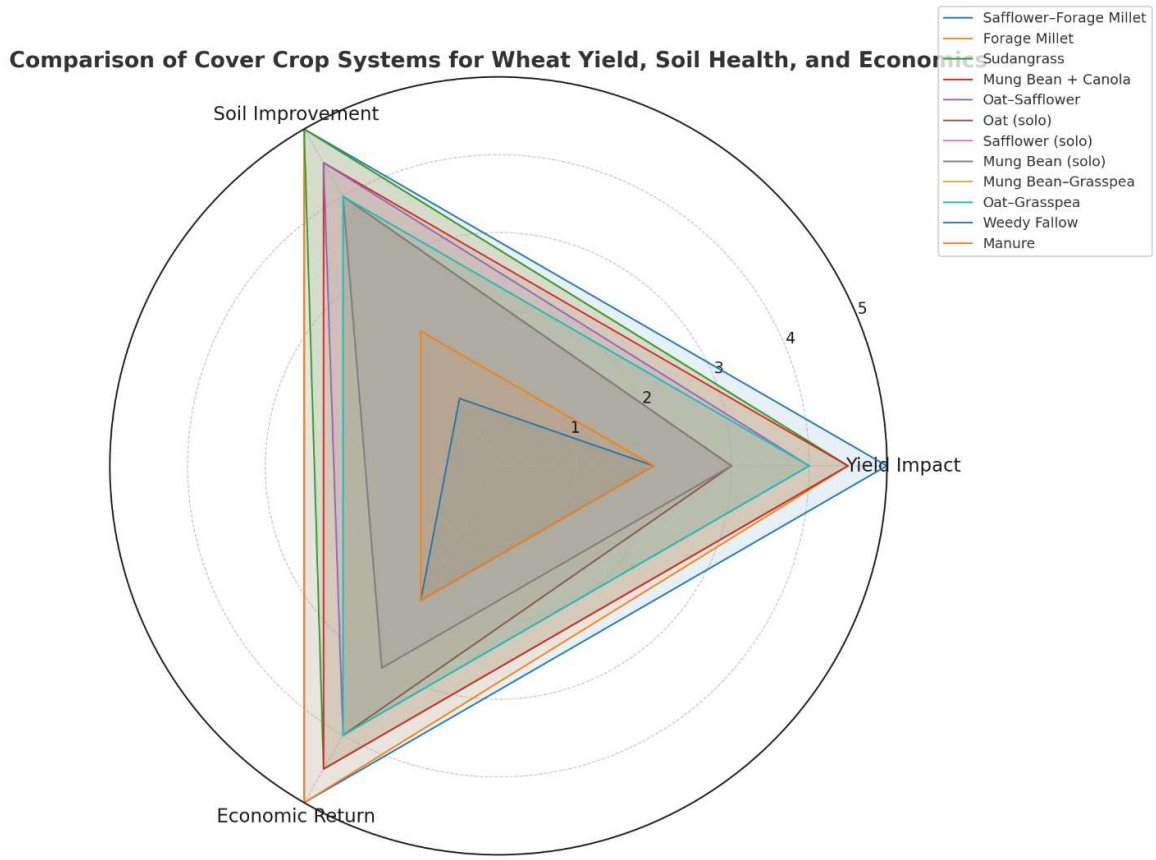
Decision Table: Ranking of Green Manure Cover Crops in Irrigated Wheat Systems

Cover Crop / Mixture	Wheat Yield Impact	Soil Improvement (SOC, structure, water)	Economic Return	Overall Rank / Recommendation
Safflower–Forage Millet (mixture)	★★★★★ (Highest yield: 8,490–10,740 kg/ha; +3,000 kg/ha over controls)	★★★★★ (High biomass, synergistic effect, BNI from millet, safflower rooting)	★★★★★ (Strongest net return, high ROI)	**#1 – Best option, strongly recommended**
Forage Millet (solo)	★★★★☆ (Yield up to 9,518 kg/ha, stable across years)	★★★★★ (BNI effect, strong SOC build-up, good water-saving)	★★★★★ (Highest profitability, ROI 73%)	**#2 – Excellent for yield + soil**
Sudangrass (solo)	★★★★☆ (Yield ~9,029 kg/ha, consistent)	★★★★★ (Highest biomass: 12 t/ha dry, 50 t/ha fresh; strong SOC)	★★★★☆ (High return but higher management cost)	**#3 – Strong yield & soil builder**
Mung Bean + Canola (mixture)	★★★★☆ (Yield ~8,918 kg/ha)	★★★★☆ (Legume N-fixation + canola root exudates)	★★★★☆ (Good return, diversified)	**#4 – Good mixture for fertility + income**
Oat–Safflower (mixture)	★★★★☆ (Strong in 2nd year; +3,434 kg/ha jump)	★★★★☆ (Delayed legacy effect)	★★★★☆	**#5 – Recommended, but delayed effect**
Oat (solo)	★★★☆☆ (Weak in year 1, strong in year 2)	★★★★☆ (Good SOC build-up, delayed)	★★★★☆	**#6 – Useful, but best with mixtures**
Safflower (solo)	★★★☆☆ (7,372–8,320 kg/ha; lower than mixtures)	★★★★☆ (Deep-rooted, improves soil)	★★★☆☆	**#7 – Useful but better in mixtures**
Mung Bean (solo)	★★★☆☆ (6,300–8,580 kg/ha)	★★★★☆ (N-fixation, improves protein content)	★★★☆☆	**#8 – Decent, but better in mixtures**
Mung Bean–Grasspea (mixture)	★★★★☆ (10,080 kg/ha in year 2)	★★★★☆	★★★★☆	**#9 – Promising legume mix**
Oat–Grasspea (mixture)	★★★★☆ (~10,070 kg/ha in year 2)	★★★★☆	★★★★☆	**#10 – Promising, especially in 2nd year**
Weedy Fallow	★★☆☆☆ (+3,400 kg/ha over clean fallow by year 4)	★☆☆☆☆ (SOC depletion, soil degradation)	★★☆☆☆ (temporary yield benefit, long-term loss)	**#27 – Emergency use only (when no irrigation available)**
Manure (applied before wheat)	★★☆☆☆ (7,710–8,120 kg/ha, inconsistent)	★★☆☆☆ (limited SOC benefit)	★★☆☆☆ (less profitable)	**#28 – Weakest option, not sustainable**

Key Takeaways

1. **Top recommendation:** *Safflower–Forage Millet mixture* (highest yield, best soil restoration, best economic return).
2. **Best solo crops:** *Forage Millet* (BNI effect, stable yield) and *Sudangrass* (biomass powerhouse).
3. **Legume mixes (Mung Bean, Grasspea, Canola):** Strong for fertility and protein improvement, slightly less for yield.
4. **Oat-based systems:** Require more than one season to show benefits (legacy effect).
5. **Avoid relying on manure or pure weedy fallow** for long-term sustainability — they underperform in soil health.

Figure- A visual summary radar chart showing which cover crops are strongest in yield, soil improvement, and economics



The radar chart comparing cover crop systems across **yield impact, soil improvement, and economic return** clearly shows that **Safflower–Forage Millet, Forage Millet, and Sudangrass** are the top-performing systems, while **Weedy Fallow and Manure** rank the lowest.